Revisiting Constraints on Fourth Generation Neutrino Masses

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Abstract

We revisit the current experimental bounds on fourth-generation Majorana neutrino masses, including the effects of right handed neutrinos. Current bounds from LEPII are significantly altered by a global analysis. We show that the current bounds on fourth generation neutrinos decaying to eW ar μW can be reduced to about 80 GeV (from the current bound of 90 GeV), while a neutrino decaying to τW can be as light as 62.1 GeV. The weakened bound opens up a neutrino decay channel for intermediate mass Higgs, and interesting multi-particle final states for Higgs and fourth generation lepton decays.

1 Introduction

One of the most natural possibilities for an extension of the standard model is a fourth copy of the three known generations of particles. These fourth generation quarks and leptons could not be very heavy, since they acquire mass from chiral symmetry breaking. They would thus be accessible at the LHC, with striking signatures even in early data.

While previous studies had argued that such fourth generation particles were incompatible with electroweak precision data [1], recent work [2] has shown that the existence of weak scale charged and neutral leptons is allowed by electroweak precision data for heavier Higgs masses, with appropriate mass splittings for the new particles. Furthermore, certain anomalies in the b-quark sector can be ameliorated by a fourth generation [3, 4, 5, 6, 7, 8]. This has led to a revival of interest in this possibility (see [9] for a review).

In light of upcoming LHC searches, it is of particular importance to understand the allowed parameter space of the fourth generation. Several experiments constrain the parameter space of fourth generation quarks. Experimental measurements at the Tevatron have set limits of 311 GeV for the t' [10], and 338 GeV for the b' [11]. Many studies have also been done of the possibility of discovering fourth generation quarks at the LHC [12, 13, 14, 15, 16, 17, 18, 19, 20]. From these studies, it appears that the LHC can discover or exclude fourth generation quarks to about a TeV.

On the other hand, constraints on the lepton sector of the new generation have not been studied in as much detail. While LEP II has placed bounds on fourth generation neutrino masses, there has as yet been no search performed at the Tevatron (Tevatron sensitivity studies for fourth generation neutrinos were performed in [21]). This is a surprising omission, since fourth generation leptons are expected to be lighter than fourth generation quarks, if the first three generations are any indication. Indeed, the fourth generation neutrino should be considerably lighter than the quarks. The fourth generation neutrino search is therefore particularly appealing.

Furthermore, the lepton sector is expected to be extremely rich in phenomenology. The reason is that the relatively high mass scale for the neutrino poses a puzzle for building models of the fourth generation. If the neutrino mass is generated by the dimension 5 operator $\frac{\nu\nu HH}{M}$, then the suppression scale M cannot be too high (in this case, less than a few TeV), and there should be new particles at this scale. The most natural assumption is that the right handed neutrino for the fourth generation is not very heavy, and that the neutrino masses are generated by the analogue of the seesaw mechanism, except that the scale of suppression is much lower. This provides a reason why the fourth generation neutrino is so much heavier than the others. It also immediately implies that any phenomenological analysis should include both the left- and right-handed neutrino. In addition the charged lepton can also potentially play a role in the phenomenology of this sector.

In this note, we will revisit the LEPII bounds on neutrino masses, taking into account the existence of both left- and right-handed neutrinos. We will not include the charged lepton in this analysis; we will return to this in future work. We find that current bounds are significantly diluted once this extra state is included.

	e, μ mode			τ mode		
N_1 mass	ϵ_{11}	ϵ_{12}	ϵ_{22}	ϵ_{11}	ϵ_{12}	ϵ_{22}
45	.162	.313	.331	.121	.149	.181
55	.188	.336	.338	.125	.151	.188
65	.224	.342	.384	.110	.147	.196
75	.251	.342	.369	.114	.149	.199
85	.234	.325	.352	.129	.155	.195

Table 1: Search efficiencies for N_1N_1, N_1N_2 and N_2N_2 processes respectively where N_1 decays to eW, μW or τW.

This has important consequences for future collider searches, as the parameter space is enlarged considerably, with new interesting signals that were not analyzed previously.

We will analyze the two-neutrino parameter space in more detail below. In section 2 we review the theory of fourth generation neutrinos, as well as their production and decay. In section 3, we review the LEP experimental searches for neutrinos, and find the efficiency of this search when applied to the more general parameter space. We then analyze the bounds imposed on the two-neutrino parameter space from these searches and show that the parameter space can be considerably enlarged. Finally, we conclude with a discussion of future directions, in particular effects on Higgs searches.

2 Review of Fourth Generation Neutrinos

We will be following the notation of [22].

We consider an extension to the standard model by a fourth generation of fermions and a right-handed neutrino. The mass term for the neutrinos can be written as

$$L_m = -\frac{1}{2}\overline{(Q_R^c N_R^c)} \begin{pmatrix} 0 & m_D \\ m_d & M \end{pmatrix} \begin{pmatrix} Q_R \\ N_R \end{pmatrix} + h.c. \tag{1}$$

where $\psi^c = -i\gamma^2\psi^*$. This theory has two mass eigenvalues

$$\begin{aligned} m_1 &= -(M/2) + \sqrt{m_D^2 + M^2/4} \\ m_2 &= -(M/2) - \sqrt{m_D^2 + M^2/4} \end{aligned} \tag{2}$$

with the corresponding eigenstates

$$N_1 = \cos\theta Q_L^c + s_\theta N_R + \cos\theta Q_L + s_\theta N_R^c \tag{3}$$

$$N_2 = -is_\theta Q_L^c + i\cos\theta N_R + is_\theta Q_L - i\cos\theta N_R^c \tag{4}$$

where we have defined the mixing angle

$$\tan\theta = m_1/m_D$$

Note in particular that $\theta = \pi/4$ corresponds to a pure Dirac state, while $\theta = \pi/2$ corresponds to a pure Majorana state (the other fermion decouples in this limit).

In addition, there is a mass term for the fourth generation lepton. We will assume that the lepton is heavier than the two neutrinos; we will therefore not include it in our analysis.

The neutrinos couple to the gauge bosons through the interaction term $L = gW_\mu^+ J^{\mu+} + gW_\mu^- J^{\mu-} + gZ_\mu J^\mu$ where

$$J^\mu = \frac{1}{2\cos\theta_W}(-c_\theta^2 \bar{N}_1\gamma^\mu\gamma^5 N_1 - 2is_\theta c_\theta \bar{N}_1\gamma^\mu N_2 - s_\theta^2 \bar{N}_2\gamma^\mu\gamma^5 N_2)) \tag{5}$$

$$J^{\mu+} = c_i\overline{(c_\theta N_1 - is_\theta N_2)}\gamma^\mu l_L^i \tag{6}$$

where c_i are analogous to the CKM matrix elements.

CM Energy (GeV)	192	196	200	202	205	207
Luminosities	26	76	83	41	83	140

Table 2: Luminosities in pb^{-1} at LEP II as a function of energy.

We now consider the possible decay modes of N_1, N_2. Since we have assumed that the fourth generation lepton is heavy, the lighter neutrino N_1 can only decay through a charged current interaction to lW, where l is a lepton of the first three generations. The relative branching ratios are set by the unknown c_i, and we will have to consider each possibility separately.

N_2, on the other hand, can decay either to lW or to $N_1 Z$. The first decay mode is suppressed by the small mixing between the fourth generation and the other three generations (which we shall assume to be much smaller than the electroweak coupling). For most masses, the second decay mode will dominate. When the mass difference between the two neutrinos goes to zero (the pseudo-Dirac limit), there is a phase space suppression of the second mode. We will assume that we do not have this extreme degeneracy and that the mode $N_2 \to N_1$ dominates. We shall impose this by assuming that the $m_2 - m_1 > 10$ GeV.

Note also that in the Dirac limit, only the CKM suppressed decay is allowed to occur, and the interference between the various contributions kills the same sign dilepton decays. This is expected since the Dirac fermion conserves fermion number. Since we are assuming that the decay $N_2 \to N_1 Z$ dominates, this interference does not occur. We therefore get same sign dilepton decays for all the parameter space we consider.

3 LEP Constraints

The existing constraints on fourth generation neutrino masses mainly come from LEP II [23]. These searches assumed that there was a single neutrino, which was either Majorana or Dirac, which decayed through a W boson, $N \to W^+ l^-$. The analysis depended on whether the lepton was e, μ or τ. If the neutrino decayed to eW or μW, the events were required to satisfy the following requirements:

1) Two isolated leptons (same flavor) with a total energy less than 0.7 E_{beam}

2) Number of jets plus isolated leptons is at least 3

3) Hadronic energy exceeds 60 GeV and charged track multiplicity larger than 3

If the neutrino decayed to τW, the event selection depended on whether the tau decayed leptonically or hadronically. For leptonic decays, the events had to pass the event selection above with the same flavor requirement relaxed. If at least one tau decayed hadronically, the event was required to satisfy

1) Number of jets plus isolated leptons is at least 4

2) Polar angle of missing momentum in the range $25^0 < \theta_{miss} < 155^0$

3) Fraction of visible energy in the forward backward region ($20^0 > \theta$ or $\theta > 160^0$) should be less than 40%.

4) All electron and muon energies less than 50 GeV.

5) Angle between most isolated track and track nearest to it should be greater than 50^0, or the angle between second most isolated track and track nearest to it should be greater than 25^0.

6) Transverse momenta of two most isolated tracks should be greater than 1.2 GeV, and at least one track must have a transverse momentum greater than 2.5 GeV.

For decay channels where the lepton is entirely e, entirely μ or entirely τ, mass exclusions were made at 90.7, 89.5, and 80.5 GeV respectively for Majorana particles and 101.5, 101.3 and 90.3 GeV respectively for Dirac particles (the Majorana mass bounds are lower then the Dirac bounds because Majorana fermion production is accompanied by an extra velocity factor in the production cross section.) Similarly, stable fourth generation neutrinos need to be fairly heavy (at least 40 GeV) to escape constraints posed by the invisible width of the Z.

We now consider the two neutrino parameter space. At LEP, the two neutrinos are produced through the Z by the processes

$$ee \to Z \to N_1 N_1 \to lWlW$$
$$ee \to Z \to N_1 N_2 \to lWlWZ$$
$$ee \to Z \to N_2 N_2 \to lWlWZZ$$

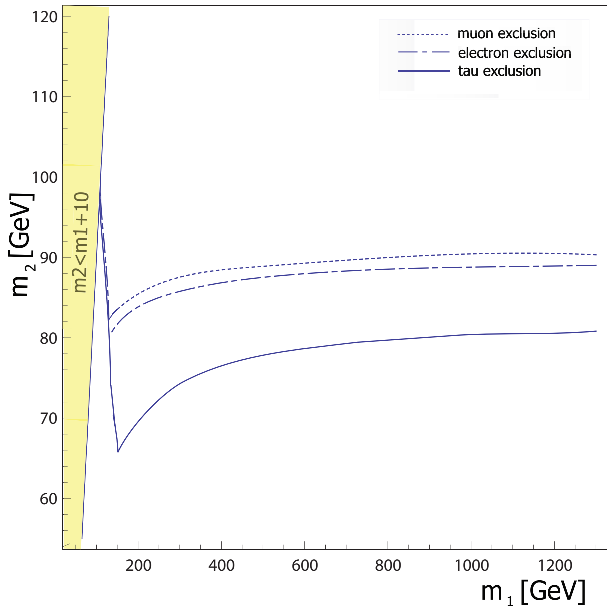

Figure 1: Bounds on m_1 and m_2 when N_1 decays to eW, μW, and τW respectively. The region above the lines is allowed.

To calculate the new constraints on this parameter space, we need to find the sensitivity of the LEP analysis to N_1N_2 and N_2N_2 production.

To find the efficiencies, we generated $ee \to N_iN_j$ events using MADGRAPH 4.4.32 [24]. The neutrinos were then decayed using BRIDGE [25], and the events were hadronized using Pythia [26]. The efficiencies of the processes were calculated by simulating events and examining how many passed the cuts described above. For the case of N_1N_1 decaying to electrons and muons, we were able to reproduce the efficiencies obtained by LEP; in particular, we obtain the same mass bound on the neutrinos in the Majorana limit. For the tau case, we had to scale our efficiencies by a factor of 1.3 to obtain the LEP efficiency (to reproduce the mass bound in the Majorana limit).

For the N_1N_2 and N_2N_2 processes, we then apply the same scaling; viz. we scaled all the processes with tau final states by a factor 1.3 to obtain our final efficiencies. We found that these efficiencies are almost independent of the mass of N_2. The final scaled efficiencies are shown in Table 1.

We note that in these analyses, we have assumed that the state N_1 decays entirely into a single species of lepton. In any more general situation, the lower bound for all efficiencies is set by the tau search, since in the leptonic decay mode, the tau search uses the same search parameters as the electron and muon final state search.

The largest factor contributing to the features of the efficiencies was the existence of a hard well isolated final state lepton. This causes the efficiencies for the detection of N_1N_2 and N_2N_2 processes to be higher that that of N_1N_1, as the decay of the heavy to light neutrino proceeds through a Z boson, which may produce additional final state leptons. We must note, however, that this will only be the case as long as the mass splitting between the two neutrino states is large enough. As the neutrino masses approach each other, the final state leptons from the offshell N_2 decay become soft, the isolated leptons are lost, and the detection efficiency drops. If the mass difference is very small, N_2 lives long enough to decay outside of the vertex detector and the efficiency for heavy neutrino detection drops precipitously. We have only explored the regions in the m_1m_2 mass plan where the mass neutrino mass difference is greater than 10 GeV, and the search efficiency for N_2 remains high. However we would expect that the least stringent mass bounds on neutrinos would actually come from the (possibly very fine-tuned) region where the neutrino mass splitting is very small.

We can now calculate the number of expected events at LEP. From the period 1999-2000, LEP collected 450 pb^{-1} of data between 192-207 GeV [27]. The luminosities at the various energies are reproduced in Table 2.

The production cross sections for these processes can be analytically calculated to be

$$\sigma_{N_1N_1} = \frac{1}{24\pi}\frac{\left(E_{cm}^2/4 - m_1^2\right)^{3/2}}{E_{cm}}\left(\frac{g\cos\theta}{\cos\theta_W}\right)^4\left((-\frac{1}{2}+\sin^2\theta_W)^2+\sin^4\theta_W\right)\frac{1}{(E_{cm}^2-m_Z^2)^2} \tag{7}$$

$$\sigma_{N_2N_2} = \frac{1}{24\pi}\frac{\left(E_{cm}^2/4 - m_2^2\right)^{3/2}}{E_{cm}}\left(\frac{g\cos\theta}{\cos\theta_W}\right)^4\left((-\frac{1}{2}+\sin^2\theta_W)^2+\sin^4\theta_W\right)\frac{1}{(E_{cm}^2-m_Z^2)^2} \tag{8}$$

$$\sigma_{N_1N_2} = \frac{1}{8\pi}\frac{p_1}{E_{cm}^3}(\cos^2\theta\sin^2\theta)\left(\frac{g}{\cos\theta_W}\right)^4\left((-\frac{1}{2}+\sin^2\theta_W)^2+\sin^4\theta_W\right)\frac{E_{cm}^2}{(E_{cm}^2-m_Z^2)^2}$$
$$(2E_1E_2+2p_1^2/3+2m_1m_2) \tag{9}$$

where in the last line we have defined

$$p_1 = \frac{\sqrt{(E_{cm}^2-(m_1+m_1)^2)(E_{cm}^2-(m_2-m_1)^2)}}{2E_{cm}} \tag{10}$$

$$E_1 = \frac{(E_{cm}^2-m_2^2+m_1^2)}{2E_{cm}} \qquad E_2 = \frac{(E_{cm}^2+m_2^2-m_1^2)}{2E_{cm}} \tag{11}$$

(note that θ in the above formulae is the mixing angle (5), not a kinematic variable.)

We now find the expected number of events and require that they be within the exclusion limits set in [23]. This produces exclusion regions in m_1-m_2 parameter space. These are shown in Figure 1.

We can understand the features of this plot as follows. The production cross section $\sigma_{N_1N_1}$ is suppressed by $\cos^4\theta$. In the Majorana limit $\frac{m_2}{m_1}\to\infty$, this factor is 1, and we return to the 1-neutrino analysis performed at LEP. As m_2 decreases, $\cos\theta$ decreases, and the production cross section is suppressed. Eventually when m_2 is small enough, the production of N_1N_2 and N_2N_2 turns on. and the total cross section again increases. The total cross section therefore first decreases and then increases as $\cos\theta$ varies from 1 to $\frac{1}{2}$; correspondingly the neutrino mass constraints first weaken and then tighten.

For very low mass differences, the decay channel $N_2\to lW$ may open up, as explained above. This means that we must include interference effects, which are model dependent since they depend on the unknown mixing angles between the fourth generation and the first three generations. For small mass differences, we may also have new effects like displaced vertices, which we have not considered. For these reasons, we have excluded from our analysis the region where the mass difference is less than 10 GeV.

By construction,when m_2 is much larger than m_1, we find the old exclusion limits for N_1. However, when m_2 is not very large, the mass bound on N_1 is significantly lowered. These new bounds are shown in Table 3.

4 Conclusions

If a fourth generation exists, relatively light righthanded neutrinos must exist in order to generate a sufficiently large neutrino mass. The existence of these extra states modifies search strategies for the leptonic sector of the fourth generation. In particular, we have shown that current LEP searches, which put strong bounds on a single Majorana neutrino, can be considerably weakened when this more general spectrum is taken into account. If the lighter neutrino decays to eW or μW, the neutrino mass limit can be reduced to about 80 GeV. In the case where the fourth generation neutrino primarily decays to τW, we find that these neutrinos may be as light as 62.1 GeV.

There are several immediate directions for further research. To complete the study of the leptonic sector, the charged lepton should also be included in the analysis. This already leads to several options for the mass spectra, with possible multilepton signals at colliders. More generally, the phenomenology of fourth generation particles with two light neutrinos is a fascinating topic for further searches. We would expect any heavy fourth generation lepton to cascade down through the neutrino mass states creating signatures with many final state leptons and missing energy. If the W-tau-neutrino coupling is dominant, we may have fourth generation pair production with decays to final states with up to 14 final state particles and a large amount of missing energy. If the fourth generation neutrinos are highly boosted, this raises the possibility of spectacular signals like lepton jets [28].

The Tevatron is also capable of searching for the fourth generation leptons directly. In recent work [21], it was shown that the Tevatron can significantly improve the LEP bounds for a Majorana neutrino, with

N_1 Decay Mode	Previous bounds	New bounds
Wτ	80.5	62.1
Wμ	89.5	79.9
W e	90.7	81.8

Table 3: Bounds on N_1 mass in GeV for the various decay channels.

a possibility of excluding neutrinos with mass up to 175 GeV. It would be very interesting to extend this analysis to the two-neutrino case, and obtain the corresponding bounds.

It should also be noted that the Majorana neutrinos decay half the time to same sign leptons (i.e. the decay products are $l^+l^+W^-W^-$). Looking for same sign leptons significantly reduced the background for the Tevatron search. LEP did not incorporate this event signature in their analysis. A reanalysis of LEP data looking for same sign lepton events also has the potential to significantly improve the reach.

The fourth generation neutrinos can also affect Higgs searches at the Tevatron and LHC. If the neutrino is near the mass limit of 62 GeV, a Higgs with mass in the range between 125 and 160 GeV will primarily decay to these neutrinos, with an unusual signal of $WW\tau\tau$ (a related analysis has been performed in [20]). It would be very interesting to incorporate this decay mode into Higgs searches at the Tevatron and LHC. We hope to return to these issues in future work.

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References

[1] C. Amsler *et al.* [Particle Data Group], Phys. Lett. B **667**, 1 (2008).

[2] G. D. Kribs, T. Plehn, M. Spannowsky and T. M. P. Tait, Phys. Rev. D **76**, 075016 (2007) [arXiv:0706.3718 [hep-ph]].

[3] T. Aaltonen *et al.* [CDF Collaboration], "First Flavor-Tagged Determination of Bounds on Mixing-Induced CP Violation Phys. Rev. Lett. **100**, 161802 (2008) [arXiv:0712.2397 [hep-ex]].

[4] V. M. Abazov *et al.* [D0 Collaboration], "Measurement of B_s^0 mixing parameters from the flavor-tagged decay Phys. Rev. Lett. **101**, 241801 (2008) [arXiv:0802.2255 [hep-ex]].

[5] W. S. Hou, M. Nagashima and A. Soddu, "Difference in B+ and B0 direct CP asymmetry as effect of a fourth Phys. Rev. Lett. **95**, 141601 (2005) [arXiv:hep-ph/0503072].

[6] W. S. Hou, M. Nagashima and A. Soddu, "Enhanced $K(L) \to \pi^0 \nu \bar{\nu}$ from direct CP violation in $B \to K\pi$ Phys. Rev. D **72**, 115007 (2005) [arXiv:hep-ph/0508237].

[7] A. Soni, A. K. Alok, A. Giri, R. Mohanta and S. Nandi, arXiv:0807.1971 [hep-ph].

[8] [The Belle Collaboration], "Difference in direct charge-parity violation between charged and neutral Nature **452**, 332 (2008).

[9] B. Holdom, W. S. Hou, T. Hurth, M. L. Mangano, S. Sultansoy and G. Unel, PMC Phys. A **3**, 4 (2009) [arXiv:0904.4698 [hep-ph]].

[10] D. Cox [CDF Collaboration and for the CDF Collaboration], arXiv:0910.3279 [hep-ex].

[11] T. Aaltonen *et al.* [The CDF Collaboration], arXiv:0912.1057 [hep-ex].

[12] V. E. Ozcan, S. Sultansoy and G. Unel, Eur. Phys. J. C **57**, 621 (2008).

[13] O. Cakir, H. Duran Yildiz, R. Mehdiyev and I. Turk Cakir, Eur. Phys. J. C **56**, 537 (2008) [arXiv:0801.0236 [hep-ph]].

[14] B. Holdom, JHEP **0708**, 069 (2007) [arXiv:0705.1736 [hep-ph]].

[15] T. Han and B. Zhang, Phys. Rev. Lett. **97**, 171804 (2006) [arXiv:hep-ph/0604064].

[16] A. Atre, T. Han, S. Pascoli and B. Zhang, JHEP **0905**, 030 (2009) [arXiv:0901.3589 [hep-ph]].

[17] F. del Aguila, S. Bar-Shalom, A. Soni and J. Wudka, Phys. Lett. B **670**, 399 (2009) [arXiv:0806.0876 [hep-ph]].

[18] F. del Aguila, J. A. Aguilar-Saavedra and R. Pittau, JHEP **0710**, 047 (2007) [arXiv:hep-ph/0703261].

[19] P. Q. Hung and M. Sher, Phys. Rev. D **77**, 037302 (2008) [arXiv:0711.4353 [hep-ph]].

[20] T. Cuhadar-Donszelmann, M. K. Unel, V. E. Ozcan, S. Sultansoy and G. Unel, JHEP **0810**, 074 (2008) [arXiv:0806.4003 [hep-ph]].

[21] A. Rajaraman and D. Whiteson, arXiv:1001.1229 [hep-ph].

[22] Y. Katsuki, M. Marui, R. Najima *et al.*, Phys. Lett. **B354**, 363-370 (1995). [hep-ph/9501236].

[23] P. Achard *et al.* [L3 Collaboration], Phys. Lett. B **517**, 75 (2001) [arXiv:hep-ex/0107015].

[24] J. Alwall *et al.*, JHEP **0709**, 028 (2007) [arXiv:0706.2334 [hep-ph]].

[25] P. Meade and M. Reece, arXiv:hep-ph/0703031.

[26] T. Sjöstrand *et al.*, Comput. Phys. Commun. **238** 135 (2001).

[27] R. Assmann *et al.* [LEP Energy Working Group], Eur. Phys. J. C **39**, 253 (2005) [arXiv:hep-ex/0410026].

[28] N. Arkani-Hamed and N. Weiner, JHEP **0812**, 104 (2008) [arXiv:0810.0714 [hep-ph]].